TECHNIQUES OF AEROSOL FORMATION

ROBERT J. ZENTNER
U. S. Army Chemical Corps, Fort Detrick, Frederick, Maryland

Referring to the fine aerial suspensions of arsenical smokes, the term "aerosol" came into use during the latter part of World War I. In this Conference, the primary interest is in aerosols composed of particles capable of causing an airborne infection, in general in the micron size range. At the lower size limit are those particles which transport single infectious microorganisms. The upper size limit is set by characteristics of the respiratory system and the hygroscopic nature of the particles.

After recognizing these qualitative restrictions on aerosols pertinent to this segment of medical science, we proceed to classification and techniques of formation. Aerosols can be created by condensation processes or by methods involving the dispersion of bulk material. In condensation processes, clouds are formed in the atmosphere. Monodisperse aerosols, i.e., aerosols composed of particles of a single size, may be formed in the laboratory by the slow and uniform condensation of vapor upon condensation nuclei. The La Mer aerosol generator (8) is a suitable device for this process but not of major interest in this Conference because of the improbability that the microorganisms could retain properties of viability and infectivity after being subjected to the molecular processes of vaporization and condensation. That does not exclude the possibility of considering the microorganisms as condensation nuclei.

We turn to the second class of methods. The dispersion or atomization class involves the subdivision of a bulk of material, either a body of liquid, a solid or an aggregate of solid particles into particles which are of the appropriate size. For liquids the formation of appropriately sized droplets may be made considerably easier by equilibration with the atmosphere. Significant size reduction may take place because of evaporation of volatile components in the slurry or dispersed material. In addition to reducing the diameter of individual droplets a considerable sharpening of the size distribution will result. For example, suppose the size distribution in an aerosol as generated is between 10 and 40 μ and a 4-fold reduction in diameter is experienced because of evaporation to equilibrate with the atmosphere. The resulting aerosol then ranges from 2.5 to 10 μ in particle size. For solids the converse may be true. Again, depending upon the nature of the solids, significant rehydration may take place with an increase in mass. There may be as much as 2.5-fold increase in diameter due to rehydration.

In any dispersing system, energy is applied to a liquid causing unstable configurations and subsequent droplet formation or is applied to disintegrate a solid or disperse a solid into fine particles. The breakup of liquids has been studied intensively with regard to specific atomizers which are in wide use in industrial applications. The basic physics of the shatter process is still incompletely known and the mechanism cannot as yet be analyzed quantitatively. In the process of atomizing or creating an aerosol from a liquid, energy is expended in three ways: creating new surface, overcoming viscous forces in deformation, and losses in inefficient application. Calculations of total surface area based upon experimentally determined particle size distributions with nonvolatile liquids indicate that at most a few per cent of the available energy is utilized in this fashion. Because of the short time involved in the formation of droplets, deformation must take place rapidly and viscous losses must therefore be large. Losses because of inefficient application of energy can only be estimated for specific cases but in air-blast atomization these losses must be large.

Green and Lane (6) have used three main classifications of atomizing devices for generating aerosols from liquids. The first is the hydraulic type. In devices of this type, liquid is forced through a small orifice, forming an unstable jet. The physical properties of the liquid and the conditions of ejection from the nozzle are important in determining the breakup of the liquid into droplets. Variations from the simple orifice are abundant. Swirl chambers are used in nozzles for oil burners, and impingement plates or pins have been used to deform the jet into a sheet of

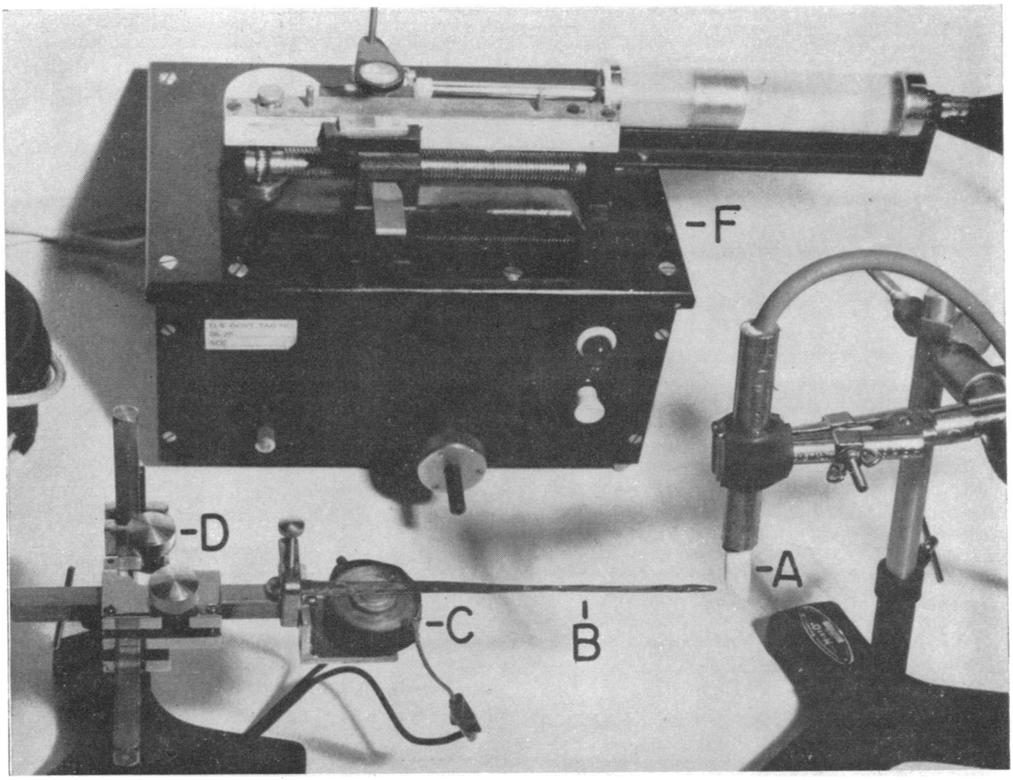

FIG. 1. *Uniform droplet generator. Arrangement for 60 cycle A.C. operation: A, Sintered glass taper; B, Vibrating reed; C, Electromagnet; D, Micromanipulator; E, Variable transformer (not shown); F, Constant feed device. 0.5×.*

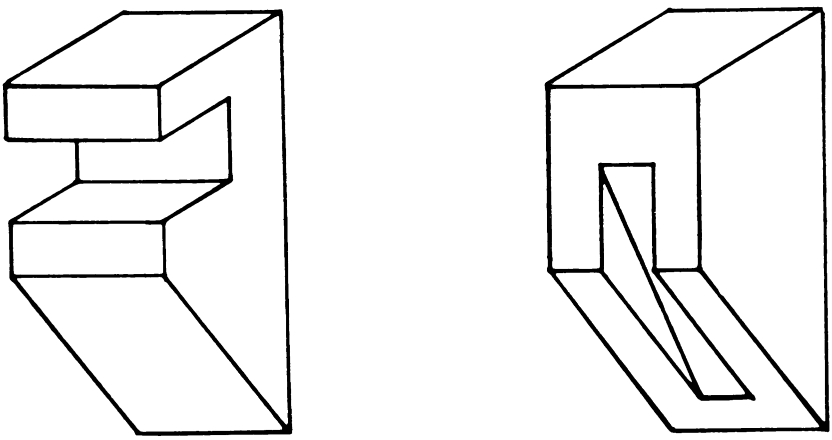

FIG. 2. *Sintered glass reservoirs for horizontal and vertical operation of vibrating reed (schematic)*

liquid before droplet formation to obtain a more acceptable size distribution of the particles in the aerosol. Typical of this class is an impingement nozzle designated the PT-12. The liquid to be atomized is forced through a small sharp-edged orifice at a pressure in excess of 1,000 lb/in^2 and impinges upon a pin located axially over the orifice. The result is that a conical sheet is formed which upon continued expansion breaks up into droplets. For a laboratory device, the liquid flow

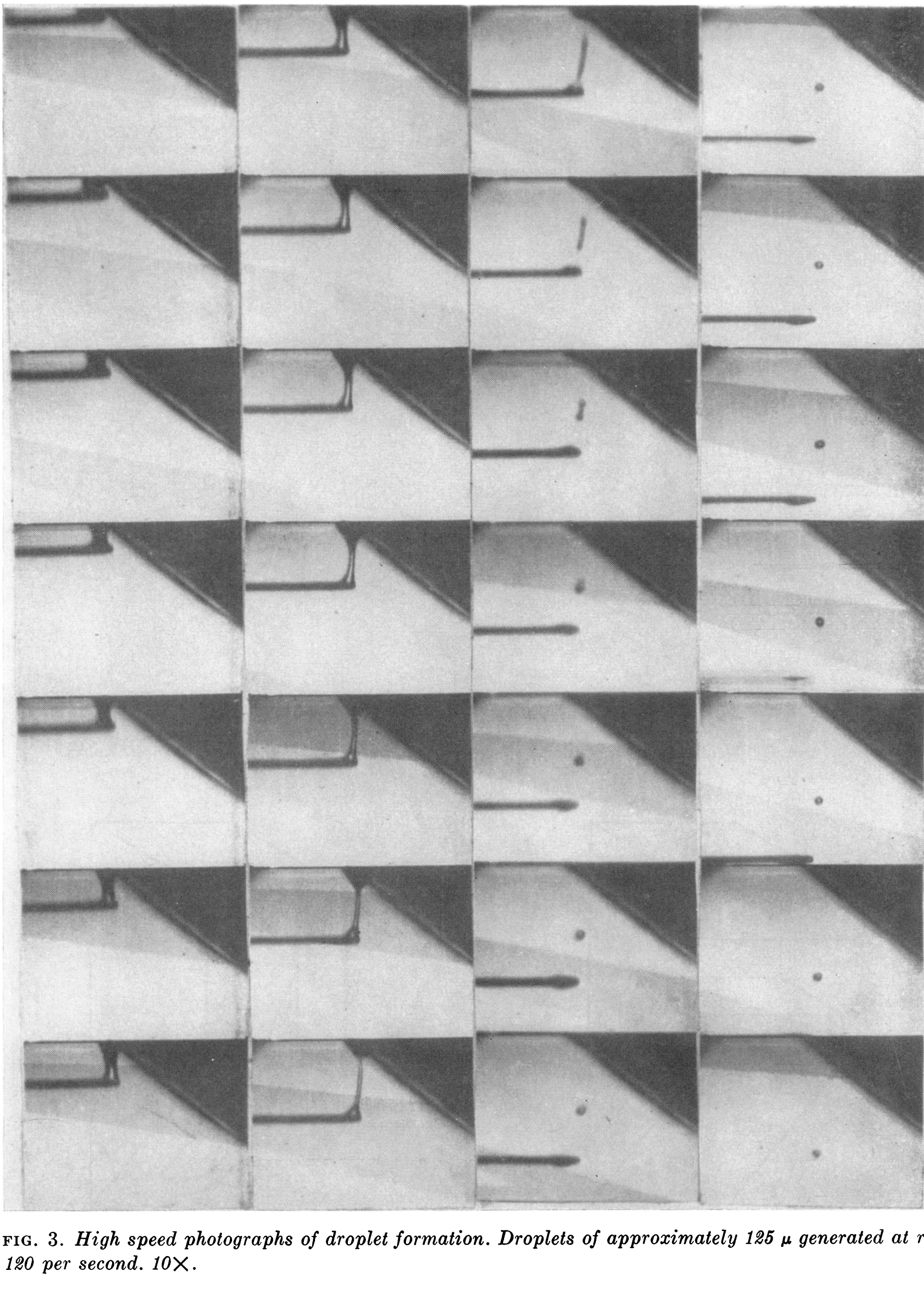

FIG. 3. *High speed photographs of droplet formation. Droplets of approximately 125 μ generated at rate of 120 per second. 10×.*

rate is relatively high, being about 300 ml/min. Approximately 15% of the material so aerosolized is converted to particles of a nominal 5-μ size range after evaporation of the water component when gelatin phosphate diluent is used. As is indicated by these numbers, the particle size distributions characteristic of hydraulic nozzles are broad and consequently most of the material

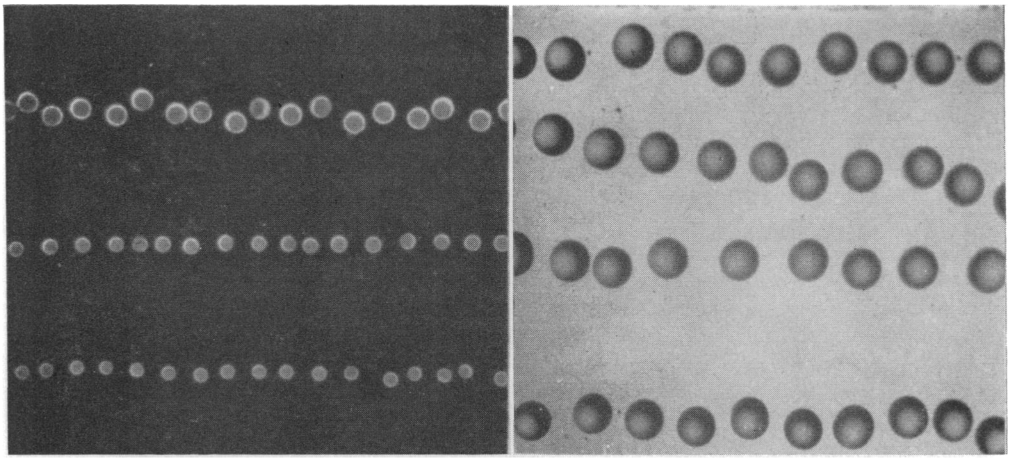

FIG. 4. *Photomicrographs of droplets produced by the uniform droplet generator. Left—Water droplets collected on magnesium oxide coated slides. 20×. Droplet diameters are 142, 113 and 85 μ. Right—N-di-butyl phthalate droplets collected on Dri-film coated slide. 60×. Droplets are 94 μ in diameter.*

aerosolized is found in particles too large to be of interest in respiratory infectivity studies.

Air-blast atomizers of the second class function by subjecting liquid emerging from a nozzle to deforming and shattering effects of a high velocity stream of gas. This type of atomization is used in the familiar DDT aerosol bomb, paint sprayers, and the now outmoded Flit-Gun. These atomizers are characterized by the fact that they produce a range of droplet sizes; however, the range is not as broad as that produced by hydraulic nozzles. In some cases the particle size distribution of the output is reduced by trapping the larger particles within the atomizer. Specific atomizers which are of use in research in airborne infection are the Collison atomizer (2) and the Vaponefrin nebulizer (1), both of which use baffles to trap the larger particles and reflux them. The cylindrical baffle of the Collison atomizer operates to limit the maximal size droplets from nonvolatile liquids to 10 μ. Using dibutyl phthalate, the Collison atomizer operated at 30 lb/in^2 yields an aerosol with a 3-μ mass median diameter; however, the mass flow rate is only 0.14 g/min. Dautreband (3) has reported extensively on the use of "obligatory liquid filtration" to obtain filtered aerosols having mass median diameters of about 0.04 μ.

The third type depends upon centrifugal action. This type has been used extensively for spray drying and humidification. In general, liquid is fed to a rapidly rotating surface which is at right angles to the axis of rotation, and because of the resulting centrifugal force, a thinning sheet of liquid is formed. The flow is in the radial direction and instabilities are introduced into the liquid sheet. Breakup into droplets ensues with the final sheet thickness dictating the predominant drop size. The spinning disk atomizer of Walton and Prewett (9) is a good example. Using a small self-balancing top driven by compressed air at rotational speeds up to several thousand revolutions per second, this atomizer subjects the thin sheet of liquid to a radial acceleration of about $10^6 \times g$. The spray formed can be made of nearly uniform drop size by reducing the liquid feed; however, it always contains a number of satellite droplets. An improved model by May (7) is capable of extracting the unwanted small satellites from the spray. When the liquid feed rate is kept below about 1 ml/min, nearly homogeneous mists of almost any size down to about 6 μ can be generated.

Other means have been used to generate aerosols from liquids. Ultrasonic means have been used to a limited degree, as has the application of high voltage to a finely drawn capillary filled with liquid, resulting in atomization. High voltage pulses have been applied to beds or reservoir of solid particles to inject the particles into small chambers for subsequent study (10).

None of the methods so far discussed can be used to obtain an aerosol of truly uniform particles. The methods have ranged from the hydraulic nozzle, capable of aerosolizing liquid materials at high rates but producing an aerosol

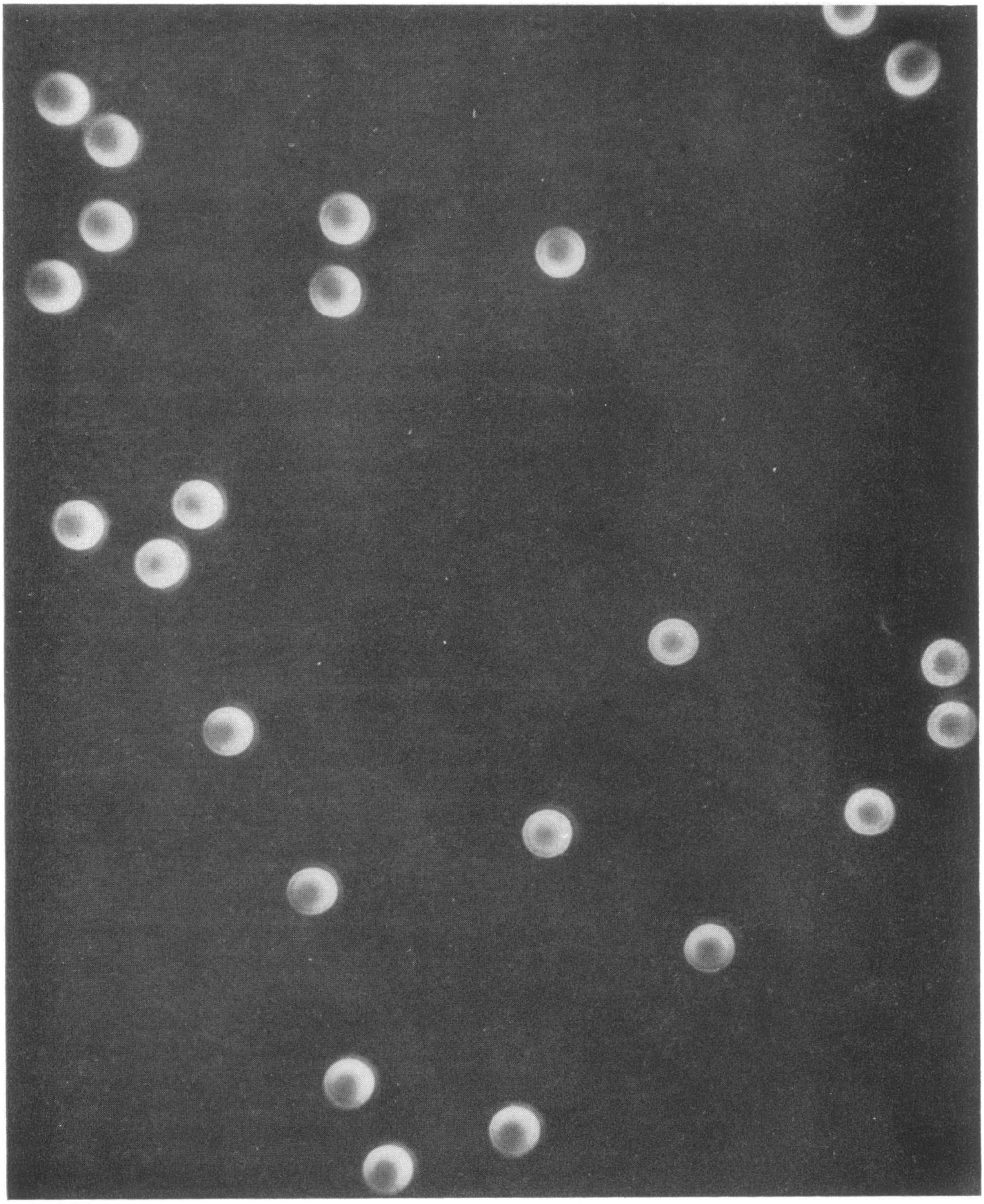

FIG. 5. *Photomicrograph of 16-μ dibutyl phthalate droplets produced by uniform droplet generator. 416×.*

with a broad distribution, to the spinning disk, which achieves a fair degree of size uniformity but at low feed rate. The production of droplets of very uniform size has attracted the interest of many investigators. True uniformity eliminates a variable which tends to confound the results of any experiment on or with aerosols. Dimmock (5) was first to report the use of vibratory action to obtain particle uniformity. He used a vibrating capillary driven by an electromagnet. Liquid forced through the capillary caused streams of droplets to be ejected at different points on the path of the vibrating tip. Each stream contained uniform droplets but different streams had different drop sizes. Davis (4) utilized the principle of vibrating action by devising a reed of spring steel tapered to a fine point and so positioned that the tip was immersed in a drop of liquid at one maximum of vibration. The reed was vibrated as Dimmock had done. Davis determined that size of the droplets thus produced was a function of the frequency of vibration, depth of penetration of the reed into the fluid supply, and the size and material of the reed. The volatility of the liquid aerosolized also played a major role in determining final drop sizes. Although the primary purposes of the vibrating reed device of Davis was to produce droplets of uniform size, this result was not realized due to inconsistencies in the level of the liquid drop relative to the reed. W. R. Wolf has modified this device to provide for a source of liquid at constant level and has thus achieved the production of truly uniform droplets. A constant level liquid supply is assured through use of a well, cut into a piece of sintered glass. The laboratory arrangement is shown in Fig. 1. Figure 2 shows sintered glass reservoirs and the trajectories of droplets produced by the vibrating reed. Figure 3 illustrates the mechanism of droplet formation. The reed withdraws a ligament of fluid from the reservoir and the ligament, after detaching from both the reed and surface of the fluid in the well, collapses due to surface tension. Thus, a droplet is formed for each penetration and withdrawal of the reed.

Figure 4 shows droplets collected. The final illustration, Fig. 5, shows 16-μ droplets of a nonvolatile liquid, dibutyl phthalate. The disadvantage of the extremely low output of this device, 120 drops/sec, is overshadowed by the uniformity of the droplets produced, and it has proved to be an extremely valuable tool in the study of aerosols and aerosol-induced infection.

Each of the methods discussed possesses certain advantages in the study of airborne infection. The hydraulic nozzle is useful to generate aerosols for the purpose of determining responses to gross clouds, and devices generating particles of uniform sizes are of greatest utility in determining particle size effects in the infection process.

Literature Cited

1. Brown, C. E., and W. R. Griffith. 1958. Syringe device for studies on bacterial and other aerosols. A. M. A. Arch. Ind. Health **18**:415–421.
2. Collison, W. E. 1935. Inhalation therapy technique. Heineman, London. 77 p.
3. Dautreband, L. 1958. Studies on aerosols. Atomic Energy Commission, Research and Development Report UR-530. Univ. Rochester Atomic Energy Project, Rochester. 590 p.
4. Davis, J. M. 1951. A vibrating apparatus for producing drops of uniform size. U. S. Dept. Agr., Div. Forest Insect Invest., Report ET-295. U. S. Bur. Ent. and Plant Quarterly, April 1951. 2 p.
5. Dimmock, N. A. 1951. Production of uniform droplets. Nature **166**:686–687.
6. Green, H. L., and W. R. Lane. 1957. Particulate clouds: dusts, smokes and mists. E. & F. N. Spon, Ltd, London. 427 p.
7. May, K. R. 1949. An improved spinning top homogeneous spray apparatus. J. Appl. Phys. **20**:932–938.
8. Sinclair, D. 1950. Formation of aerosols, p. 77–80. *In* Handbook on aerosols, U. S. Office of Scientific Res. and Dev., National Defense Research Comm. summary. U. S. Govt. Printing Office, Washington, D. C.
9. Walton, W. H., and W. L. Prewett. 1949. The production of sprays and mists of uniform drop sizes by means of spinning-disc type sprayers. Proc. Phys. Soc. (London) **62B**:341–350.
10. Wuerker, R. F., H. Shelton, and R. V. Langmuir. 1959. Electrodynamic containment of charged particles. J. Appl. Phys. **30**:342–349.